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DETERMINING THE CP NATURE OF A NEUTRAL HIGGS BOSON AT THE LHC

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Abstract

We demonstrate that certain weighted moments of $t\bar{t}h$ production can provide a determination of the CP nature of a light neutral Higgs boson produced and detected in this mode at the CERN LHC.

1 Introduction

It is well-known [1, 2] that detection of a Higgs boson h with couplings roughly like those of the Standard Model (SM) Higgs (ϕ^0) will be possible at the LHC, the detection mode depending upon the mass m_h. If $m_h \lesssim 130 \, \mathrm{GeV}$, the primary techniques for observing such an h rely on $gg \to h$, $W^\star \to Wh$, and $gg \to t\bar{t}h$, with $h \to \gamma\gamma$ and, for the latter two modes, $h \to b\bar{b}$. If the h is part of a larger (non-SM) Higgs sector, deviations of the Wh and $t\bar{t}h$ production rates from SM expectations will be present, but difficult to interpret. A direct determination of whether the h is CP-even (as predicted for the SM ϕ^0 and the minimal supersymmetric model h^0) would be especially crucial to unravelling the situation. The only procedure proposed to date for directly determining the CP nature of a light h employs proton beam polarization asymmetries that are only sufficiently large if proton polarization implies substantial polarization for the colliding gluons in the $gg \to h$ process [3]. Here, we demonstrate that certain weighted moments of the cross section for $t\bar{t}h$ production are sensitive to the relative magnitudes of the CP-even and CP-odd coupling coefficients c and d (respectively) in the $t\bar{t}h$ interaction Lagrangian, $\mathcal{L} \equiv \bar{t}(c + id\gamma_5)th$. The accuracy with which these moments can be measured experimentally at the LHC (assuming an accumulated, detector-summed luminosity of $L = 600 \, \mathrm{fb}^{-1}$) is sufficient that the CP-even SM Higgs boson can be shown to be inconsistent with an equal mixture of CP-odd and CP-even components at the $\sim 1.5\sigma - 2\sigma$ statistical level, and inconsistent with a purely CP-odd state at the $\gtrsim 7\sigma$ statistical level.

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2 The Technique

Consider a general quark-antiquark-Higgs coupling of the form $\overline{Q}(c + id\gamma_5)Qh$, where c and d are both taken to be real; c and d determine the CP-even and CP-odd components of the coupling, respectively. By explicit calculation, it can be demonstrated that the spin-averaged cross sections for $gg \to Q\overline{Q}h$ and $q\overline{q} \to Q\overline{Q}h$ production contain no terms proportional to cd. However, they do contain terms proportional to both $(c^2 + d^2)$ and $(c^2 - d^2)$. Since the $(c^2 - d^2)$ terms are multiplied by m_q^2,[1] sensitivity to $(c^2 - d^2)$ terms is only significant if m_q^2 is of the same order as the other invariant masses-squared for the subprocess. The latter are fairly large, being set by the scale m_h^2, implying that only $t\overline{t}h$ production will have substantial sensitivity to $(c^2 - d^2)$. For convenience, we adopt the conventional normalization of $(c^2 + d^2) = 1$ in our tabulations below.

In order to isolate the $(c^2 - d^2)$ terms in the production amplitude-squared in a manner that is free of systematic uncertainties associated with the overall production rate, we compute the ratio:

$$\alpha[\mathcal{O}_{CP}] \equiv \frac{\int [\mathcal{O}_{CP}] \{ d\sigma(pp \to t\overline{t}X)/dPS \} \, dPS}{\int \{ d\sigma(pp \to t\overline{t}X)/dPS \} \, dPS} , \tag{1}$$

where $\mathcal{O}_{CP}$ is an operator designed to maximize sensitivity of α to the $(c^2 - d^2)$ term. We have found that a variety of simple operators offer substantial sensitivity to $(c^2 - d^2)$. The best of those that we have examined are

$$
\begin{aligned}
a_1 &= \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\overline{t}} \times \widehat{n})}{|(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\overline{t}} \times \widehat{n})|} & b_1 &= \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\overline{t}} \times \widehat{n})}{p_t^T p_{\overline{t}}^T} & b_2 &= \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\overline{t}} \times \widehat{n})}{|\vec{p}_t||\vec{p}_{\overline{t}}|} \\
a_2 &= \frac{p_t^x p_{\overline{t}}^x}{|p_t^x p_{\overline{t}}^x|} & b_3 &= \frac{p_t^x p_{\overline{t}}^x}{p_t^T p_{\overline{t}}^T} & b_4 &= \frac{p_t^z p_{\overline{t}}^z}{|\vec{p}_t||\vec{p}_{\overline{t}}|}
\end{aligned}
\tag{2}
$$

where $p_{t,\overline{t}}^T$ denote the magnitudes of the t and $\overline{t}$ transverse momenta. In Eq. 2, $\widehat{n}$ is a unit vector in the direction of the beam line and defines the z axis. One can also employ the y-component analogues of a_2 and b_3. Since all these operators will have somewhat different systematic uncertainties, it will be useful to analyze the CP properties using all of them (and, perhaps, others as well). Higher moments of the operators were also considered, but in all cases the linear moments were the most sensitive to changes in the c vs. d weighting.

The critical question with regard to the usefulness of a given α is the accuracy with which it can be measured relative to the predicted changes in α as a function of the CP nature of the h. In general, there will be background as well as $t\overline{t}h$ signal contributions in any $t\overline{t}X$ channel ($X = \gamma\gamma$ or $b\overline{b}$). We define α_S and α_B to be the value of α as defined in Eq. 1 for the signal and background cross sections on their own. We also define

$$\beta[\mathcal{O}_{CP}] \equiv \frac{\int [\mathcal{O}_{CP}]^2 \{ d\sigma(pp \to t\overline{t}X)/dPS \} \, dPS}{\int \{ d\sigma(pp \to t\overline{t}X)/dPS \} \, dPS} , \tag{3}$$

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[1]This is in addition to the m_q^2 factor contained in the c^2 and d^2 squared couplings themselves.

and the β_S and β_B values of β for the signal and background individually. Then, one finds that the experimental error for α_S is given by

$$\delta\alpha_S = S^{-1/2}\left[\beta_S - \alpha_S^2 + \frac{B}{S}\left(\beta_B - 2\alpha_B\alpha_S + \alpha_S^2\right)\right]^{1/2}, \qquad (4)$$

where S and B are the total number of signal and background events, respectively, in the $t\bar{t}X$ channel being considered. This result assumes that B, α_B and β_B can be experimentally measured (using data with M_X not in the vicinity of m_h) and/or calculated with high precision. Note that $\beta = 1$ for the a_i operators.

Table 1: $t\bar{t}\gamma\gamma$ channel α_B and β_B values, assuming $m_h = 100\,\text{GeV}$.

$\mathcal{O}_{CP}$	a_1	b_1	b_2	a_2	b_3	b_4
α_B	-0.863	-0.796	-0.249	-0.698	-0.404	0.130
β_B	1	0.806	0.127	1	0.332	0.411

Table 2: Values of α_S and β_S for the $t\bar{t}h$ production, assuming $m_h = 100\,\text{GeV}$, for the cases: $c = 1, d = 0$; $c = d = 1/\sqrt{2}$; $c = 0, d = 1$. Also given is $S^{1/2}\delta\alpha_S$ in the limit $B = 0$.

$\mathcal{O}_{CP}$	a_1	b_1	b_2	a_2	b_3	b_4
$c = 1, d = 0$						
α_S	-0.810	-0.718	-0.269	-0.619	-0.359	0.292
β_S	1	0.736	0.151	1	0.308	0.376
$S^{1/2}\delta\alpha_S$	0.586	0.469	0.280	0.785	0.424	0.539
$c = d = 1/\sqrt{2}$						
α_S	-0.742	-0.654	-0.243	-0.562	-0.327	0.228
β_S	1	0.707	0.139	1	0.302	0.372
$S^{1/2}\delta\alpha_S$	0.671	0.528	0.283	0.827	0.442	0.566
$c = 0, d = 1$						
α_S	-0.486	-0.407	-0.147	-0.335	-0.200	-0.005
β_S	1	0.593	0.096	1	0.272	0.371
$S^{1/2}\delta\alpha_S$	0.874	0.654	0.272	0.942	0.482	0.609

Let us now focus on the $X = \gamma\gamma$ channel. Detection of a Higgs boson in the $t\bar{t}\gamma\gamma$ final state was originally proposed in Ref. [4] and has been thoroughly studied by both the ATLAS and CMS collaborations in their Technical Proposals [5, 6]. The final state employed is that in which one t decays semi-leptonically, while the other decays hadronically. This allows identification of the t vs. the $\bar{t}$, and reconstruction

of the transverse momenta of both the t and $\bar{t}$. This is already sufficient for defining $a_{1,2}$ and $b_{1,3}$ in Eq. 2. The $b_{2,4}$ operators of Eq. 2 require knowledge of the full t and $\bar{t}$ three momenta. For the hadronically decaying t, the three jets can be used for this determination. Determination of the z component of momentum of the leptonically decaying t is subject to the usual two-fold ambiguity in determining the z component of the momentum of the unobserved neutrino using the missing transverse energy, $m_\nu = 0$, and the known value of m_t. The algorithm in which p_ν^z is chosen so as to minimize the overall rapidity of the $t\bar{t}h$ system yields the correct solution a large fraction of the time.

We first present the values of α and β for signal and background, for the various different $\mathcal{O}_{CP}$ operators listed in Eq. 2, assuming a Higgs boson mass of $m_h = 100\,\text{GeV}$. These values include mild cuts on the outgoing t, $\bar{t}$ and photons of: $|y_{t,\bar{t},\gamma}| < 4$, $p_\gamma^T > m_h/4$. In actual practice, the detector collaborations must compute the expected numbers using their full cuts and resolutions. Results for α_B and β_B are given in Table 1, and results for α_S and β_S are given in Table 2 for several choices of c, d. Also given are the values of $S^{1/2}\delta\alpha_S$ in the limit of zero background. These latter values give a first indication of the relative sensitivity of the various $\mathcal{O}_{CP}$ operators to different values of c, d.

Table 3: $t\bar{t}\gamma\gamma$ channel, $m_h = 100\,\text{GeV}$: discrimination powers in the limit $B = 0$.

$\mathcal{O}_{CP}$	a_1	b_1	b_2	a_2	b_3	b_4
$D_1/\sqrt{S}$	0.117	0.137	0.091	0.073	0.076	0.118
$D_2/\sqrt{S}$	0.554	0.663	0.436	0.362	0.374	0.551

In order to better interpret these results, we define the two discrimination powers:

$$D_1 \equiv \frac{|\alpha_S(c = 1, d = 0) - \alpha_S(c = d = 1/\sqrt{2})|}{\delta\alpha_S(c = 1, d = 0)},$$
$$D_2 \equiv \frac{|\alpha_S(c = 1, d = 0) - \alpha_S(c = 0, d = 1)|}{\delta\alpha_S(c = 1, d = 0)},$$

$$(5)$$

which indicate the ability of these observables to separate the SM-like case of $c = 1, d = 0$ from the equal mixture case, $c = d = 1/\sqrt{2}$, and from the pure CP-odd case of $c = 0, d = 1$. These definitions of $D_{1,2}$ are those appropriate if the observed Higgs boson is CP-even (so that it is appropriate to use $\delta\alpha_S(c = 1, d = 0)$ in computing the experimental error).[2] Values for $D_{1,2}/\sqrt{S}$ are tabulated in Table 3

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[2]If the h is pure CP-odd, D_2 should be defined using $\delta\alpha_S(c = 0, d = 1)$; if it is an equal CP-even/CP-odd mixture, D_1 should be defined using $\delta\alpha_S(c = d = 1/\sqrt{2})$.

in the limit where $B = 0$ (no background). From this table, it is apparent that the operators a_1, b_1, b_2 and b_4 will be most useful, b_1 probably being the best, both in that it has the largest discrimination power, and also in that it can be constructed without use of z-component momenta.

Table 4: $t\bar{t}\gamma\gamma$ channel, $m_h = 100\,\mathrm{GeV}$: the discrimination powers $D_{1,2}$ for $S = 130$ and $B = 21$.

$\mathcal{O}_{CP}$	a_1	b_1	b_2	a_2	b_3	b_4
D_1	1.26	1.47	0.97	0.78	0.81	1.21
D_2	5.97	7.10	4.67	3.87	3.97	5.65

Of course, in practice we must include the background in order to obtain the true value of $\delta\alpha_S$, see Eq. 4. Let us focus on the case where the h has SM-like couplings and ask how well we can measure α_S in this case. For this purpose, we employ the results from the CMS experimental Technical Proposal, Figure 12.8 (in which $L = 162.5$ fb^{-1} is assumed), scaled to the current standard benchmark in which it is assumed that each detector (ATLAS and CMS) will separately accumulate an integrated luminosity of $L = 300$ fb^{-1}, corresponding to a total detector-summed luminosity of $L = 600$ fb^{-1}. For our estimates we will sum events in a $5\,\mathrm{GeV}$ interval centered at $M_{\gamma\gamma} = m_h = 100\,\mathrm{GeV}$. From the above-referenced Fig. 12.8, one obtains, after rescaling, $S = 259$ and $B = 42$ for the sum of the $W\gamma\gamma$ and $t\bar{t}\gamma\gamma$ modes. At the LHC, these two modes contribute almost equally, and so we divide these numbers in half to obtain the $t\bar{t}\gamma\gamma$ mode results of $S = 130$ and $B = 21$. To quantify our ability to discriminate the SM case of $c = 1, d = 0$ from the $c = d = 1/\sqrt{2}$ and $c = 0, d = 1$ cases, we compute D_1 and D_2. The resulting numerical values for $D_{1,2}$ are given in Table 4 and indicate the level of statistical significance at which an observed CP-even h could be said to *not* be (1) an equal mixture of CP-odd and CP-even or (2) a purely CP-odd state. These values may be somewhat optimistic in that the above rates are those obtained before reconstructing the t and $\bar{t}$. However, because of the cleanliness of the $t\bar{t}\gamma\gamma$ final state, we do not anticipate a large event rate loss for such reconstruction.

As anticipated, the operators a_1, b_1, b_2 and b_4 provide the best discrimination. For the best single operator, b_1, discrimination from the $c = d = 1/\sqrt{2}$ case is only achieved at the $\sim 1.5\sigma$ level. To reach the more satisfactory 3σ level would require of order four times as much integrated luminosity. Discrimination between the purely CP-even case and the purely CP-odd case would be possible using b_1 at a high level of statistical significance, $\sim 7\sigma$. Better statistical significance in both cases can be achieved to the extent that the different operators are sensitive to different aspects of the t and $\bar{t}$ distributions in the final state. In particular, b_4 is primarily sensitive to the $t, \bar{t}$ longitudinal momenta distributions, as distinct from the transverse momenta distributions that determine b_1. Simply combining

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the statistics for these two different moments would imply that $c = 1, d = 0$ could be distinguished from $c = d = 1/\sqrt{2}$ at nearly the 2σ level, assuming the $L = 600\,\text{fb}^{-1}$ SM-like event rate. In reality, the experimental groups would undoubtedly obtain the best level of discrimination by studying the likelihood that a particular c, d mixture fits their data in an overall sense (without assuming knowledge of normalization).

A second possible channel for this type of analysis is the $X = b\overline{b}$ channel (*i.e.* $t\overline{t}b\overline{b}$ final state). The signal event rate is much larger than in the $t\overline{t}\gamma\gamma$ final state, but there are large backgrounds. This channel for Higgs discovery was first explored in Refs. [7, 8], and has been studied by the ATLAS and CMS collaborations with generally encouraging results. These analyses isolate a signal by demanding that one of the t's decay semi-leptonically, and that three or four b-quarks be tagged. The expected b-tagging efficiency and purity at high luminosity are sufficiently large that statistically significant signals for a SM-like h can be achieved. In Ref. [5], with $L = 100\,\text{fb}^{-1}$ and using 3-b-tagging, event rates are large enough that a roughly 5σ signal is seen for $m_h \sim 100\,\text{GeV}$, despite a small $S/B \sim 1/40$ signal to background ratio. The 4-b-tagging results of Ref. [7] yield a cleaner $S/B \sim 1/2$, but S is also reduced so that $S/\sqrt{B}$ for $L = 100$ fb^{-1} is at most increased to $S/\sqrt{B} \sim 8-10$. (This latter study is not a full experimental simulation, and it is quite possible that these larger $S/\sqrt{B}$ values are too optimistic.) Neither of these analyses demands that the t-quarks be reconstructed, as would be required in order to construct the $\mathcal{O}_{CP}$ operators considered here. Such reconstruction could well improve the S/B ratios (in particular, by largely eliminating the combinatoric backgrounds), but undoubtedly at further sacrifice of signal event rate. Nonetheless, it seems probable that, for the combined ATLAS+CMS benchmark luminosity of $L = 600$ fb^{-1}, $S/\sqrt{B} \geq 5$ can be achieved after full t-quark reconstruction. We assume that after such reconstruction the only significant background will be from the irreducible $t\overline{t}b\overline{b}$ background process. (This is clearly the case if 4-b-tagging is employed.) In analyzing the experimental error on the determination of α_S for the different $\mathcal{O}_{CP}$ operators, we then need only compute the α_B and β_B values for the irreducible $t\overline{t}b\overline{b}$ background.

Table 5: $t\overline{t}b\overline{b}$ channel α_B and β_B values, assuming $m_h = 100\,\text{GeV}$.

$\mathcal{O}_{CP}$	a_1	b_1	b_2	a_2	b_3	b_4
α_B	-0.552	-0.478	-0.177	-0.395	-0.239	0.241
β_B	1	0.642	0.122	1	0.284	0.375

The values of α_B and β_B for the cuts $|y_{t,\overline{t},b,\overline{b}}| < 4$ and $p^T_{b,\overline{b}} > m_h/4$ are given in Table 5. The corresponding signal reaction α_S and β_S values for the various $\mathcal{O}_{CP}$ operators are unchanged from the results appearing in Table 2. Although

the cuts that will be required in the eventual analysis will be far more complex, the changes in α_S, β_S, α_B and β_B are unlikely to be so large as to invalidate the estimates obtained below.

Given α_S, β_S, α_B, and β_B, it is straightforward to compute the signal rate S for a SM-like Higgs that would be required to achieve $D_1 = 2$ (that is to discriminate a pure CP-even coupling from an equal CP-even/CP-odd mixture at the 2σ statistical level) as a function of B/S. The results are easily summarized. For $B/S \sim 1$, $D_1 = 2$ requires $S \sim 700$ (~ 600), equivalent to $S/\sqrt{B} \sim 26$ (~ 24), using $\mathcal{O}_{CP} = b_1$ (b_4). For $B/S \sim 50$, $D_1 = 2$ requires $S \sim 20{,}000$ ($\sim 15{,}000$), equivalent to $S/\sqrt{B} \sim 20$ (~ 17), for $\mathcal{O}_{CP} = b_1$ (b_4). The S values for b_4 are a bit smaller than for b_1, but probably not enough to compensate for inaccuracies associated with the need to use longitudinal momenta in constructing the former. Note the approximate rule that, for large B/S, $S/\sqrt{B} \sim 20$ is inevitably required to achieve $D_1 \sim 2$ (using b_1). The signal event rate required for $D_2 = 2$, $i.e.$ to distinguish a purely CP-even Higgs from a purely CP-odd Higgs at the 2σ level, is only about $1/20$ that needed to achieve $D_1 = 2$ (for a given B/S). Indeed, $D_2 \sim 2$ is achieved whenever we have a $S/\sqrt{B} \sim 4-5$ Higgs boson signal!

The above rules arise because $D_{1,2}$ scale as $S/\sqrt{B}$ for large B/S, see Eq. 4. Considering both the $\gamma\gamma$ and $b\overline{b}$ channels and both D_1 and D_2, we find, at large B/S,

$$\begin{aligned}
\gamma\gamma: \quad & D_1 = 2\frac{S/\sqrt{B}}{13}, \quad D_2 = 2\frac{S/\sqrt{B}}{2.7} \\
b\overline{b}: \quad & D_1 = 2\frac{S/\sqrt{B}}{22}, \quad D_2 = 2\frac{S/\sqrt{B}}{4.4}
\end{aligned} \tag{6}$$

when employing the operator b_1 (alone). In fact, the $S/\sqrt{B}$ values required for a given $D_{1,2}$ value are remarkably independent of B/S once $B/S \gtrsim 2$. For example, in the $t\overline{t}b\overline{b}$ channel, if $B/S \sim 2$ then $D_2 = 2$ is achieved for $S/\sqrt{B} \sim 5$. Of course, these large B/S scaling laws are not likely to be relevant for the $t\overline{t}\gamma\gamma$ channel, since $B/S \ll 1$ is the general rule there. Once $B/S \ll 1$, $D_{1,2}$ scale as $\sqrt{S}$: in the limit of $B = 0$, one simply uses Table 3 to obtain the S required for a given $D_{1,2}$.

Overall, the $t\overline{t}b\overline{b}$ channel will probably not be as useful as the $t\overline{t}\gamma\gamma$ channel in the case of a SM-like CP-even Higgs boson. However, for a non-SM-like Higgs boson, $BR(h \to \gamma\gamma)$ might be too small to yield an observable signal in the $t\overline{t}\gamma\gamma$ final state, whereas $BR(h \to b\overline{b})$ will generally be large and an observable signal in the $t\overline{t}b\overline{b}$ channel will be possible so long as the $t\overline{t}h$ coupling is not significantly suppressed compared to SM strength. The most difficult example is the case of a purely CP-odd A^0. The absence of the $W^+W^-A^0$ coupling implies very small $BR(A^0 \to \gamma\gamma)$. In a two-Higgs-doublet model of type-II, the $t\overline{t}A^0$ ($b\overline{b}A^0$) coupling is $\propto \cot\beta$ ($\propto \tan\beta$), where $\tan\beta$ is the ratio of the vacuum expectation values of the two neutral Higgs doublet fields [1, 2]. In the preferred $\tan\beta > 1$ region of parameter space, the $t\overline{t}A^0$ production cross section, proportional to $\cot^2\beta$, is suppressed, but $BR(A^0 \to b\overline{b})$ is large (for m_{A^0} below $2m_t$). With $L = 600$ fb^{-1}, it might prove possible to achieve $S/\sqrt{B} \sim 5$ for $\tan\beta \lesssim 2$, which (assuming large

B/S and employing $\delta \alpha_S(c = 0, d = 1)$ for b_1 from Table 2 in defining D_2) would imply $D_2 \sim 1.6$. This would at least add support to the indirect evidence for a large CP-odd component deriving simply from the absence of observable W+Higgs and $t\bar{t}\gamma\gamma$ channel signals.

3 Final Remarks and Conclusions

In this letter, we have shown that weighted moments of the $t\bar{t}h$ production cross section can provide a rough but direct (cross section normalization independent) determination of the CP nature of a light Higgs boson at the LHC. In the $t\bar{t}\gamma\gamma$ final state, if we employ the best single weighting operator that does not depend upon the longitudinal momenta of the t quarks, then a SM-like Higgs boson (pure CP-even) can be distinguished from a Higgs boson that is an equal mixture of CP-odd and CP-even at the $\sim 1.5\sigma$ statistical level with about 130 signal events (assuming $B/S \ll 1$). This is roughly the number obtained for a combined ATLAS+CMS luminosity of $L = 600 \, \text{fb}^{-1}$ (assuming that the required t-quark reconstruction does not cause large losses in this final state). About 240 signal events (after t-quark reconstruction) are needed to achieve 2σ discrimination. These same numbers of events would distinguish the purely CP-even Higgs from a purely CP-odd Higgs at the $\sim 7\sigma$ and $\sim 10\sigma$ level, respectively. If the best operator depending upon t-quark longitudinal momenta can also be employed, the above statistical significances would increase by about 40%.

In the $t\bar{t}b\bar{b}$ channel, typically characterized by $B/S \gtrsim 1$ (possibly $\gg 1$), 2σ discrimination between a pure CP-even Higgs and one with an equal mixture of CP-odd and CP-even components requires $S/\sqrt{B} \sim 20$, which would in general be very difficult to achieve (except for a Higgs with enhanced $t\bar{t}A^0$ coupling — requiring $\tan\beta < 1$ in the CP-violating type-II two-Higgs-doublet model). However, distinguishing between purely CP-even and purely CP-odd coupling at the $\gtrsim 2\sigma$ level is possible whenever $S/\sqrt{B} \gtrsim 4$, that is, whenever the Higgs boson can be detected.

If both the $t\bar{t}\gamma\gamma$ and $t\bar{t}b\bar{b}$ channels yield a useful level of discrimination, statistics in the two channels can be combined to further improve the overall discrimination level.

Although our analysis has made use of rather simplified cuts, we do not believe that these results depend very much on the cuts. Nonetheless, the experimental groups should compute the weightings defined in Eqs. 1 and 3, for both the $t\bar{t}\gamma\gamma$ and $t\bar{t}b\bar{b}$ channels, using their full simulation, including the necessary t-quark reconstruction.

A more detailed discussion of the implications of these results for a general CP-violating two-Higgs-doublet model will appear in a later paper [10].

4 Acknowledgements

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